1959

Observations on the behavior of continuously reinforced concrete pavements in pennsylvania, Highway Research Board Bulletin, 238, (1959), (Available from HRB), Reprint No. 159 (59-14)

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OBSERVATIONS ON THE BEHAVIOR

OF

CONTINUOUSLY REINFORCED CONCRETE PAVEMENTS

IN

PENNSYLVANIA

by

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Report 256.8

1958

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Bethlehem, Pennsylvania

SYNOPSIS

This paper summarizes the results of three years of sponsored research on continuously reinforced concrete pavements as conducted by the Fritz Engineering Laboratory of Lehigh University.

Test data and conclusions based upon instrumentation, physical measurements, and observations of two current pavement projects are reviewed, and a general pattern of behavior for continuous pavements is established.

Some of the weaknesses found in existing pavements are described and given consideration in suggestions for design and construction improvements in continuous pavements.

INTRODUCTION

The first continuously reinforced concrete pavement in Pennsylvania was constructed in October of 1956, and a second pavement was completed in July of 1957. The construction details, instruments installations, and early behavior of these test pavements have been described in earlier reports presented to the Highway Research Board at their annual meetings in 1957 and 1958.

Through the joint efforts of the Testing Laboratory of the Pennsylvania Department of Highways and the Fritz Engineering Laboratory of Lehigh University, a considerable amount of information has been obtained from these projects. Much of this is in the form of data collected periodically by physical measurements at the pavement surface, and electronic instrument readings taken from transducers within the concrete, the granular base course, and the supporting soil.

At regular thirty-day intervals during the past twenty-six months, gage data have been collected from a single instrumented test section in the pavement constructed in 1956. The same schedule of data collection has been maintained for sixteen months on the second pavement, where four instrumented test sections are under observation. With each test section providing forty gage readings, approximately 3600 separate measurements have been obtained from these five gaged sections in the two test pavements.

In addition to the gage readings at the instrumented sections, a series of other measurements has been made in order to provide a record of the behavior of both pavements throughout their entire two-mile length. Crack surveys, end movement measurements, surface roughness recordings, and other informative data have been collected.

Several tests on continuously reinforced pavements and similar concrete structures had been conducted prior to the test program in Pennsylvania. The information available from these tests was studied in order to anticipate pavement behavior and to plan a practical measurement scheme which would provide the greatest amount of information with a reasonable number of installed gages and limited field testing personnel.

It is believed that a complete history of the phenomena associated with the formation and behavior of transverse cracks would allow a much better understanding of reinforced pavements and possibly provide specific design information. For this reason, a concentration of instrumentation was installed at a structurally weakened section in the pavement where a transverse crack would occur.

Shortly after the first pavement was constructed, it was apparent that the measurement scheme which had been selected was satisfactory and could add materially to the existing knowledge on continuous pavements. Some of the first results of the investigation seemed to be contrary to the generally accepted theories, but it was found that these results were not unreasonable, and instead, established an excellent quantitative relationship between reactions within the pavement, surface measurements, and general pavement behavior.

The results from the second pavement project and a series of closely controlled laboratory tests, have added sufficient evidence to support these earlier findings.

Rather than presenting detailed test data from individual gage measurements, this report will deal primarily with the general behavior of the pavements under test and the more conclusive information that is required for the establishment of design criteria for all continuous pavements.

In presenting this information, the authors do not wish to imply that additional investigation of such pavements is unnecessary. The refinements required for optimum design can be developed only by continued field testing and laboratory research.

PAVEMENT BEHAVIOR

There are five major force producing and potentially damaging influences which act upon all concrete pavements regardless of their design. The ultimate success of a pavement constructed to a particular design may be judged by its ability to resist or respond to these controlling influences with a minimum of distress and deterioration.

A better understanding of the mechanics, magnitude and relationship of these influences in a continuously reinforced concrete pavement will result if, at first, each of the five is considered as an individual occurrence.

1. Shrinkage

During the process of curing, the concrete decreases in volume, and increases in strength, while bond develops between the concrete and the reinforcement. What is believed to be the result of this combined action is shown in Figure 1, where a single longitudinal reinforcing bar and the concrete within its effective influence area are considered.

Some shrinkage occurs in all of the concrete, but the volume reduction is not uniform throughout the entire mass. In shrinking, the concrete flows along the path of least resistance from areas of low tensile strength toward those of higher tensile strength. Some of the weaker areas may result from poorly mixed concrete, but more often they originate where minimum bond with the reinforcement offers the least resistance to shrinkage flow.

Shrinkage reduces the transverse cross-sectional area of the beam without developing any significant tensile stresses in the concrete, and because of this a major portion of the total shrinkage occurs in this plane.

Longitudinal shrinkage of the beam is opposed by the base friction, end anchorage, tensile strength of the concrete, and any strain resistance of the reinforcement that may be transferred to the concrete through the developing bond.

Bond strength is not constant along the reinforcement, but develops in a fairly regular pattern; reaching maximum and minimum strength at space intervals dictated by the combined influence of the concrete mixture, reinforcement perimeter, rate of curing, and base friction.

In areas where bonding with the reinforcement occurs, the tensile strength of the cross section is increased in proportion to the bond strength. As the concrete continues to cure, shrinkage flow is toward these bonded areas and away from areas where the bond is less effective. This subjects the concrete between the better bonded areas to a pulling force which may exceed the tensile strength of the concrete and cause it to rupture.

Even if the tensile stresses do not develop sufficiently to cause rupture, the cured concrete within each affected area will contain a residual stress concentration maintained by the final bond with the reinforcement.

If the full width of a pavement is considered, the developed stress pattern becomes more complex. When several reinforcements are placed parallel in a pavement, a stress pattern similar to that shown in Figure 2 will result.

The spacing and magnitude of the residual stress concentrations along each individual reinforcement will vary, due to normally encountered minor inconsistencies in materials and construction procedures. Since each stress concentration originates independently, it is only when the increasing magnitude of the stress enlarges the area of influence that the stress pattern in an adjacent parallel reinforcement is affected. A shrinkage crack will occur where the random coincidence of longitudinal stress concentrations develop a transverse plane of weakness in the pavement and the combined tension forces exceed the tensile strength of the concrete at this plane.

Many of the numerous shrinkage-induced stress concentrations developed in a pavement lack the required force and/or the longitudinal coincidence of occurrence to cause transverse cracking. They remain as areas of constantly changing force potential, where cracks may occur if the pavement is subjected to the additional tension necessary to exceed the balance relationship between the concrete and the reinforcement.

2. Temperature

This is the most formidable force to which continuously reinforced pavements are subjected. It is responsible for constantly changing the conditions of stress and strain during construction and throughout the useful life of the pavement.

Since the pavement develops anchorage near each end, the center portion has no opportunity for over-all longitudinal movement. A sudden decrease in temperature produces tensile strains which may exceed the elastic range and creep response rate of the concrete. When this occurs, a crack will develop along a transverse plane of weakness in the pavement. This crack will increase in width until the tensile forces developed in the reinforcement at the crack exceeds the tensile strength of the concrete at another plane, and a new crack is formed.

As a crack pattern develops in the pavement, each individual section between existing cracks will respond as a single isolated unit with fixed ends. New transverse cracks will open in highly stressed areas and the number of separated units will be increased. This process will continue until the force of contraction is insufficient to cause further rupture of the concrete.

Under sustained stress, such as that resulting from the mean seasonal temperature, the concrete will creep. This reduces the possibility of new cracks and tends to transfer some of the stress from the concrete to the reinforcement.

When rising temperature causes the pavement to expand, compressive forces developed between the end anchorages may become very high. Most of this expansion is absorbed by creep and elastic straining of the reinforced concrete, but under extreme conditions the ends of the pavement may lose effective anchorage and be pushed outward. The extent of this pavement elongation, or "growth", is dependent upon several factors, and probably may be controlled by alterations in future pavement design.

3. Moisture

The initial water-cement ratio of the concrete affects the strength and durability of the pavement. Proper proportioning of ingredients can regulate and control these effects.

Free water or excessive capillary moisture beneath the pavement may result in heaving during very cold weather, causing extensive damage, but proper drainage and subgrade design can minimize this danger.

In addition to these more obvious and controllable effects of moisture, there are other subtle influences which are environmental in nature, significant in effect and practically impossible to control.

Concrete is pervious to water, and will increase in volume when moisture is absorbed. Inversely, when moisture is removed, the volume of the concrete will decrease. This phenomenon will continue to influence the behavior of the concrete throughout the life of a pavement, and is independent of the initial shrinkage associated with curing.

In addition to its general influence upon the total longitudinal stress development in a continuous pavement, this moisture-induced volume change may, under some conditions, produce additional localized influences.

The bottom of the pavement, in direct contact with the sub-base, is subjected to the constant moisture of the earth, while the top surface is intermittently subjected to rain and high humidity, or the drying effects of the sun and wind. Surface dryness causes an uneven distribution of moisture in the concrete, and results in a tendency for the pavement sections to warp and lift up at the cracked ends. Increased tension in the reinforcement and traffic wheel loads oppose the upward movement and tend to restrain the pavement in its original position. Since the pavement lacks base support at the warped ends, this increased tension may cause additional cracks to occur.

Warping may account for the occasional occurrence of a second crack very near the end of an older cracked section. This second crack will occur near a point where bond has been sufficiently retained to resist further straining of the unbonded reinforcement across the original crack.

The uneven distribution of moisture in a pavement is evident in the gradual increase in the width of cracks as they extend upward from the sub-base to the surface. Examination of cores cut from the pavement, indicate that many cracks which have a considerable surface width may be entirely closed below the level of the reinforcement. When this condition exists, infiltration of small particles of foreign matter may completely fill the crack and assist in its eventual stabilization.

Serious damage to the pavement does not result when water freezes in transverse cracks if these cracks do not exceed 1/32-inch in width. The small expansion incurred in the freezing of such a thin layer of water is elastically absorbed by the adjacent concrete with very little increase of strain in the reinforcement.

4. Foundation

A highway foundation should furnish adequate support for the static weight of the pavement structure and the normal dynamic loads imposed by traffic. This support should remain sound under all weather conditions and for the life of the pavement.

Much has been accomplished toward improving highway foundations, but for many practical and economic reasons, pavements are constructed upon foundations which are certainly not ideal.

While poor foundations are not recommended, continuous pavements are inherently less susceptible than other concrete pavements to many of the damaging influences associated with foundation weakness. The shorter spaced cracked sections permit greater longitudinal flexibility of the total pavement, and the continuous reinforcement allows slight pavement settlement without resulting in pumping or vertical off-set between the individual cracked sections.

Friction opposes any movement between the pavement and its foundation. (Fig.3). Near the free ends of a continuous pavement this friction develops to the extent that an effective anchorage is established. The pavement extending from the point of anchorage to the free end, will continue to change length with changing environmental conditions, but the pavement inside the anchorage must maintain a fixed length unless the anchorage is destroyed. Over a very long period of time, sustained high compression within the pavement may cause a gradual increase in its total length, but this slight movement has a relatively insignificant effect upon the general strain pattern.

When complete anchorage establishes fixed points near each end of a pavement, most stresses and strains which develop between these points are controlled in the vicinity of their origin.

The stress in the steel and the concrete at comparable points, is normally about equal in magnitude throughout the fixed length of the pavement, and is dependent upon localized straining to maintain this equality. In effect, each individual cracked section has fixed ends maintained by the reinforcement, and this section expands and contracts about its own geometric center. This enables the pavement to respond to changing conditions of stress and strain as a localized function, and it also reduces the absolute movement of cracked sections and resultant base friction to practical insignificance.

5. Wheel Loads

All pavements are subjected to the forces of dynamic loading imposed upon them by moving traffic. Flexible pavements are designed to respond to these forces and rigid pavements to resist them, but under heavy wheel loads and adverse environmental conditions, both pavement types may suffer some degree of damage. When a local failure occurs in a pavement surface, the constant pounding of traffic usually brings about rapid deterioration and repairs are necessary.

Continuous pavements, while falling in the general classification of rigid pavements, incorporate some of the more desirable design features of both types. The short segmented concrete sections allow some deflection of the pavement from surface loading, but the longitudinal reinforcement maintains continuity between these segments, and within the elastic recovery range of the steel, limits the deflection. Residual stresses throughout the pavement provide a reserve of potential strain which may be released to prevent excessive tension in the reinforcement under changing vertical load conditions.

Continuous pavements show a natural tendency for self-preservation by actively resisting damage from wheel loads. When properly designed, they should be practically immune from structural distress caused by normal traffic loads, and have a very high overload safety factor.

PAVEMENT DESIGN

A thorough understanding of the major influences controlling the behavior of a continuous pavement is necessary in order to establish optimum design specifications.

In theory, if these several influences could be correctly correlated in all possible combinations of their magnitude, duration, and coincidence of occurrence, it would be possible to predict their effects upon a pavement and produce an ideal design. However, a lack of precise values for the formidable array of encountered variables makes this approach extremely difficult and of doubtful practical value.

Design based upon experience alone, requires years of observations of experimental pavements which eventually may prove to be over-designed or structurally unsound. Some useful design limitations have been established by this method, but an unwillingness to risk weak pavements on public highways has limited large scale field testing.

Laboratory testing with small specimens or even full scale pavement sections, can be very difficult to conduct, and may result in misleading information if environmental influences are not properly simulated.

During the past three years, several sponsored projects at Lehigh University have permitted a wide approach to the problems of continuous pavement design. Useful information has been obtained from many sources. Theories have been carefully checked with field and laboratory test results. By combining theory, field testing, and laboratory research with engineering experience, it has been possible to develop the following basic design principle.

In transverse cross-section, the yield strength of the total longitudinal steel reinforcement must be greater than the tensile strength of the total concrete. For design purposes, the tensile strength of concrete may be taken as 1/10 its compressive strength, unless tests with the concrete to be used indicate a need to alter this very conservative ratio.

The logic of this rather simple principle may be shown by explaining the process of reasoning which has led to its development.

Failures in continuous pavements usually occur at a transverse crack which has opened to an excessive width and lost the aggregate interlock of the concrete. While a crack 1/16-inch wide may close in warm weather without apparent adverse effect, greater pavement integrity is assured if the maximum cold weather crack width is held to 1/32-inch or less.

A crack will occur where the tensile strains in a pavement exceed the elastic and creep response range of the concrete at a structurally weak transverse plane. After a crack develops, the reinforcement becomes the only connection between two separate sections of pavement and will respond to subsequent straining without the influence of continuous concrete.

When the reinforcement is extremely weak, as compared to the tensile strength of the concrete, any additional strain in the pavement will tend to mobilize at the crack, causing the reinforcement to yield and thereby increasing the width of the crack. The crack will continue to increase in width with increasing strain, and new cracks will occur only at widely separated intervals regulated primarily by sub-base friction.

When the tensile yield strength of the total reinforcement and the ultimate tensile strength of the concrete cross-section are relatively equal, strains across each crack remain well within the elastic range of the reinforcement. Under these conditions, when a pavement is subjected to additional straining, the resulting total tension is only slightly relieved by the elastic straining of the reinforcement at cracks. This additional strain in the pavement upsets the force balance at stress concentrations and new cracks develop across these weakened planes. This process of transverse cracking will continue to relieve the strain as it develops, and prevent earlier formed cracks from opening to an excessive width. Hence, the control of cracking becomes a function of the concrete and reinforcement and is dependent upon their relative strength.

The transverse crack pattern, or cracks per unit length is not a dependable criterion in evaluating the soundness or potential life of a continuous pavement. Two pavements of identical design, but constructed and cured under different conditions of temperature or humidity, may develop very different crack patterns. They may be equally sound and the crack widths in both pavements may be approximately the same. On the other hand, two pavements, differing only in percentage of reinforcement, may develop very similar crack patterns, yet the average maximum cold weather crack width in one may be 0.01-inch and as much as 0.08-inch in the other.

The residual stress condition of the new concrete, at a time when the first high tensile stresses of temperature contraction become operative, has a predominate influence on the number of cracks that occur in a unit length of continuously reinforced pavement. While there is a relationship between the width of formed cracks and the number of cracks per unit length, this relationship is neither direct nor constant. Unpredictable variations in the sequence, duration, and magnitude of the early tensile stresses must be considered as controlling factors in the relationship.

It is important to remember that the creep potential of concrete is such that, under favorable conditions, most of the straining in a continuous pavement could occur without causing cracks. Although the creep rate of the concrete is often exceeded by the strain rate of the total pavement, both are mutually influential in their effect upon a developing crack pattern and upon crack widths.

Since crack width is ultimately the principal criterion for soundness, and is a function of the relative strength of the concrete and its reinforcement, pavements should be designed accordingly.

Based upon present knowledge and available materials, the following specifications are recommended as a very close approach to an optimum design for continuous pavements.

<u>Foundation</u> - Three-inch thick granular base course upon stable, well drained and compacted native soil.

<u>Pavement Dimensions</u> - Eight inches thick, twelve feet wide and any length desired.

<u>Concrete</u> - Air entrained, with a twenty-eight day compressive strength of 4000 psi.

<u>Longitudinal Reinforcement</u> - Reinforcing steel with a minimum yield of 60 000 psi placed at mid-depth, and comprising 0.7 per cent of the pavement cross-section. Until research proves otherwise, each individual reinforcement member should not exceed one-half square inch in cross section area, and longitudinal continuity of reinforcement should be maintained by a thirty-diameter over-lap at the ends.

Curing - The completed pavement may be cured by any conventional method which assures good quality concrete.

A pavement constructed to this conservative design should respond satisfactorily to the most adverse combinations of force-producing influences, and should remain sound for a prolonged period of time without requiring major repairs.

Continuous pavements with 0.5 per cent reinforcement have been constructed in Pennsylvania, and while their performance has been satisfactory, it is believed that they represent the lowest limit to which reinforcement may be safely reduced. Since each 0.1 per cent reduction in reinforcing steel reduces the paving cost approximately $0.35 per square yard, the possibility of an occasional repair must be justified by the saving in initial construction costs.

End movement of these pavements with 0.5 per cent reinforcement has been small. The finger type expansion joints on the Route 111 project have opened and closed within a one-half inch travel range during the annual temperature cycles and have indicated a gradual pavement elongation of one-quarter inch during two and one-half years of service. The seasonal motion will continue at about the present rate, but it is believed that the pavement "growth" will decrease each year until the total pavement becomes stabilized.

Although research at Lehigh University has primarily involved pavements which were reinforced with deformed bars, preliminary tests have indicated that most other high yield steel reinforcements with reasonable bond-developing qualities may be used with equal success. Specifications may be altered to suit the characteristics of the steel if the recommended ratio of relative strength of the steel and concrete is maintained.

OBSERVATIONS AND CONCLUSIONS

Research which involves the investigation of a product for the purpose of development and improvement must necessarily be concerned with its weaker and less desirable qualities. Consequently, in making recommendations for improvements, reports on such an investigation will emphasize these weaknesses while any superior qualities, which require no improvement, may be generally ignored.

To some extent, this has been the case with research on continuously reinforced concrete pavements. Several recent reports, including those from Lehigh University, have presented information and photographs which tend to deal mainly with the evidence of pavement distress. Quite often it is not clearly indicated whether this distress came about because of a weak design, poor workmanship, or other conditions that could be equally destructive to other types of highway pavements.

Continuous pavements, when compared with other types, offer several distinct advantages. While their simplicity of construction and initial cost are very similar to those of conventional concrete pavements, their low maintenance costs, long life, and smooth riding surface give them a definite advantage.

The two-mile length of four-lane continuous pavement on Route 111 near York, Pennsylvania, has provided an excellent opportunity for comparison with the conventional jointed design used in the remaining portion of this heavily traveled highway. Two years after construction, both types of pavement are in good condition, but the smoother riding qualities of the continuous pavement are definitely noticeable. There has been no evidence of distress in the continuous pavement and it has not required any maintenance. Practically no new cracks have developed during the past year, and many of the existing cracks are gradually stabilizing.

Figure 4 - first presented at the 1958 Highway Research Board Meeting and herein extended to December 1958 - shows the relationship between air temperature, crack width, and average strain in the six gaged reinforcing bars at an instigated transverse crack as recorded every thirty days throughout the past two years.

During this period of time only two of the original thirty-six wire resistance strain gages installed on the reinforcement have become inoperative, and the electrical resistance to ground has remained high under all environmental conditions.

Figure 5 shows the minimum and maximum individual strain values used to obtain the average reinforcement strain shown in Figure 4. Although this pavement contains the minimum reinforcement believed to be practical, it should continue to demonstrate the several advantages of concrete pavements constructed with continuous steel reinforcement.

In the past, pavements have been constructed as inert slabs with adequate thickness to resist local damage from direct wheel loads. They have been at the mercy of their environment and almost totally dependent upon the foundation to maintain their original vertical alignment and general structural integrity.

It is believed that future pavements will be designed with the inherent potential ability to successfully oppose all normally encountered forces which will constantly act to destroy their usefulness.

The authors believe that continuously reinforced concrete pavements, even in their present state of development, meet the requirements for future highway construction and that they are definitely superior to the more conventional designs now in general use. It seems that highway engineers are beginning to accept the randomly spaced narrow transverse cracks as evidence of proper pavement behavior and to realize that they are not indicative of pavement distress which will soon require repairs. While these cracks, with their slightly worn edges, are visible by close inspection, the motorist is unable to detect them as he drives over the surface of the highway.

The first continuous concrete pavements were constructed about twenty years ago, and their unexpected durability has been largely responsible for the current renewal of interest in their use.

It is hoped that the research now being conducted will result in a wide acceptance of this type of pavement as a means of providing superior highways, and that it will not require another twenty years for this to occur.

ACKNOWLEDGMENT

The authors wish to express their appreciation to the U.S. Bureau of Public Roads, the Pennsylvania Department of Highways, and the American Iron and Steel Institute for their sponsorship of the continuous pavement projects at Lehigh University. Many of the men within these groups have contributed valuable information and ideas to the projects.

We gratefully acknowledge the assistance of the entire technical staff of the Fritz Engineering Laboratory in conducting field tests and laboratory research.

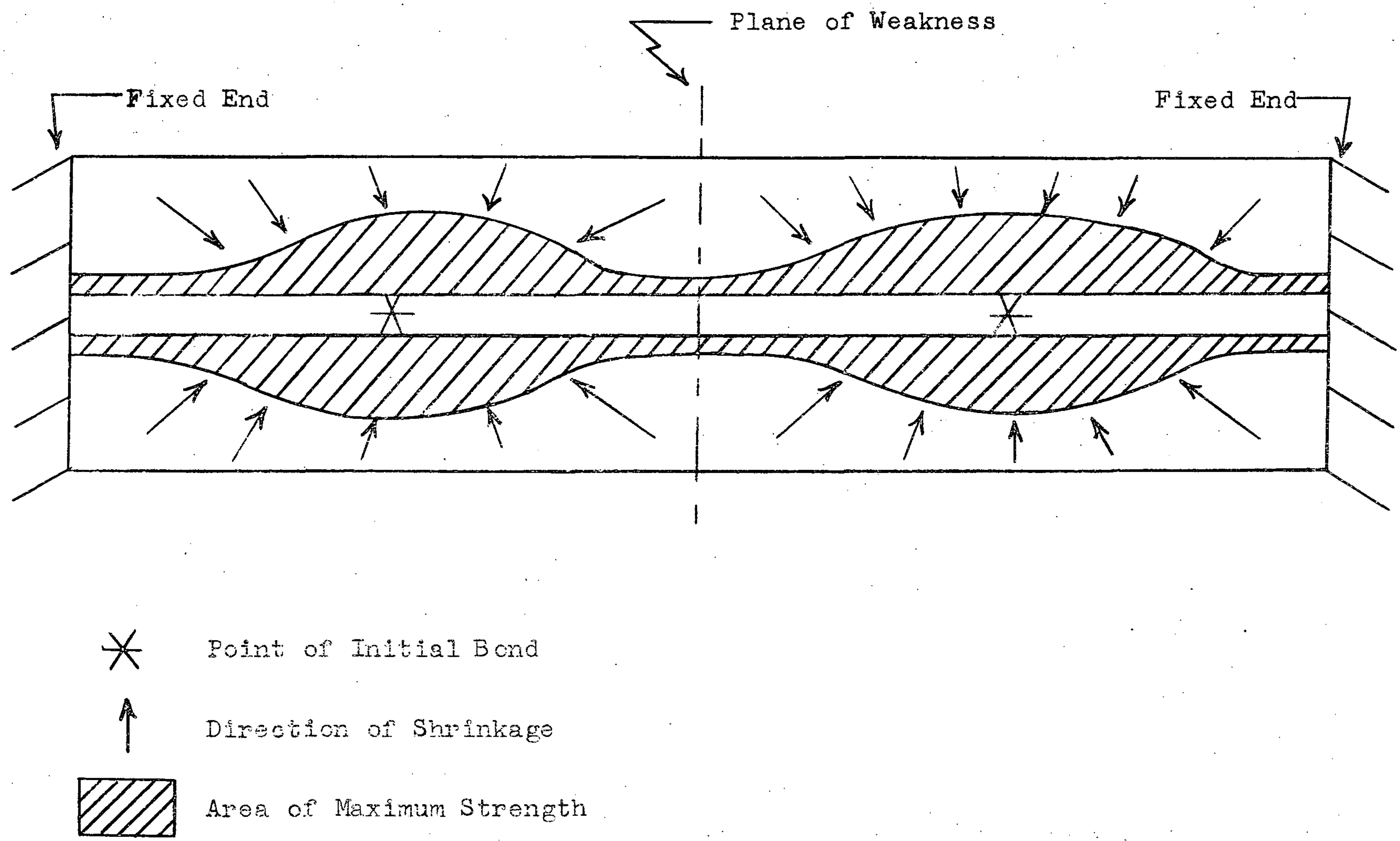

Plane of Weakness
Fixed End
Fixed End
Point of Initial Bond
Direction of Shrinkage
Area of Maximum Strength

FIGURE 1

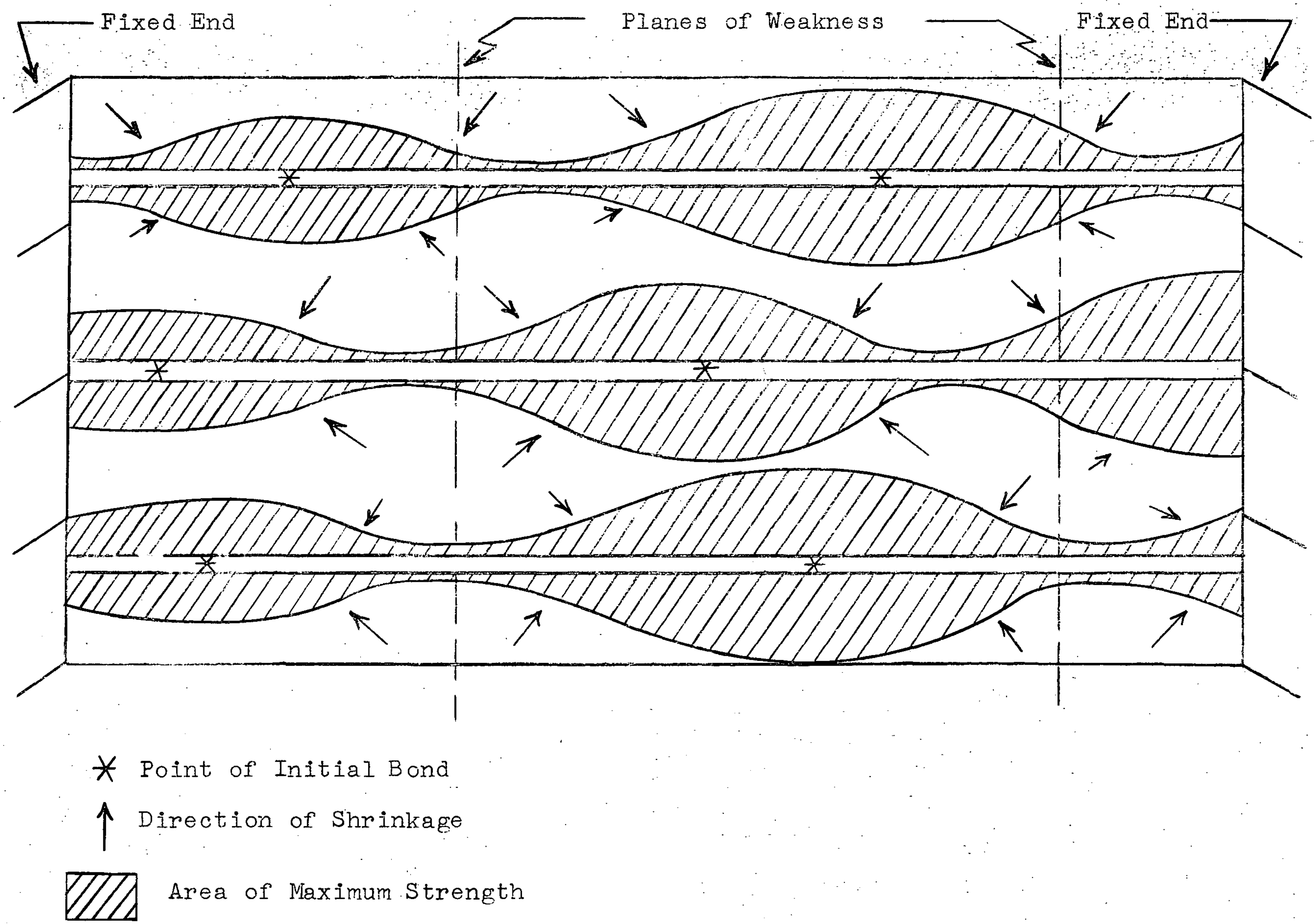
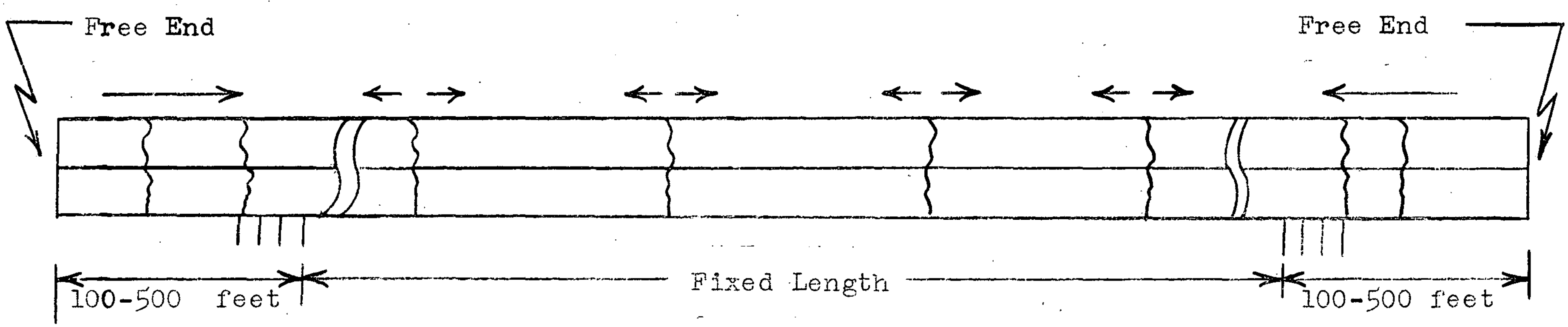

Fixed End
Planes of Weakness
Fixed End
Point of Initial Bond
Direction of Shrinkage
Area of Maximum Strength

FIGURE 2



PAVEMENT RESPONSE TO CONTRACTION FORCES

(Expansion Forces Will Reverse The Direction Of Strain)

FIGURE 3

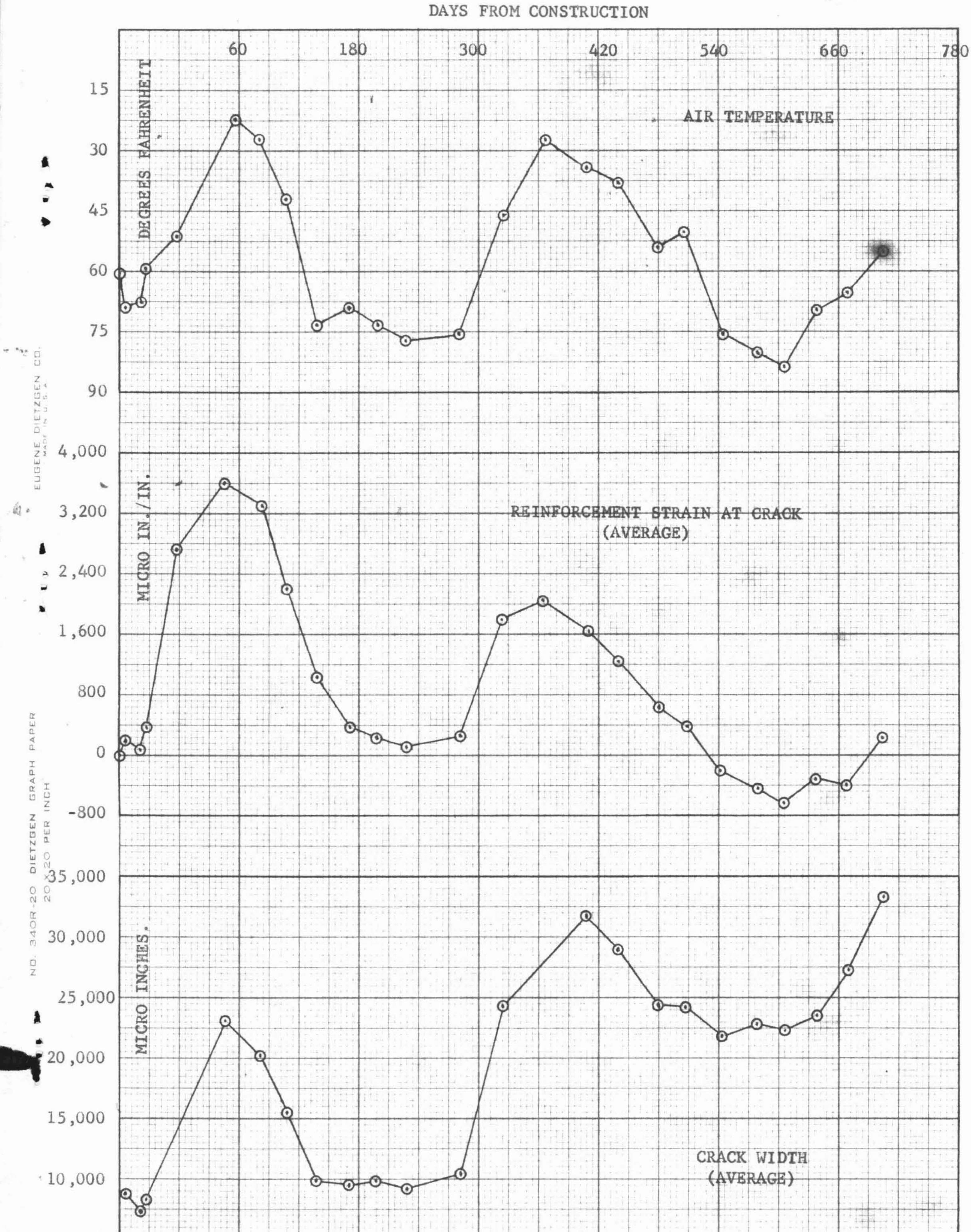

DAYS FROM CONSTRUCTION
60
180
300
420
540
660
780
DEGREES FAHRENHEIT
15
30
45
60
75
90
AIR TEMPERATURE
MICRO IN./IN.
4,000
3,200
2,400
1,600
800
0
-800
REINFORCEMENT STRAIN AT CRACK
(AVERAGE)
MICRO INCHES.
35,000
30,000
25,000
20,000
15,000
10,000
5,000
CRACK WIDTH
(AVERAGE)
EUGENE DIETZGEN CO.
MADE IN U.S.A.
NO. 340R-20 DIETZGEN GRAPH PAPER
20 X 20 PER INCH

FIGURE 4

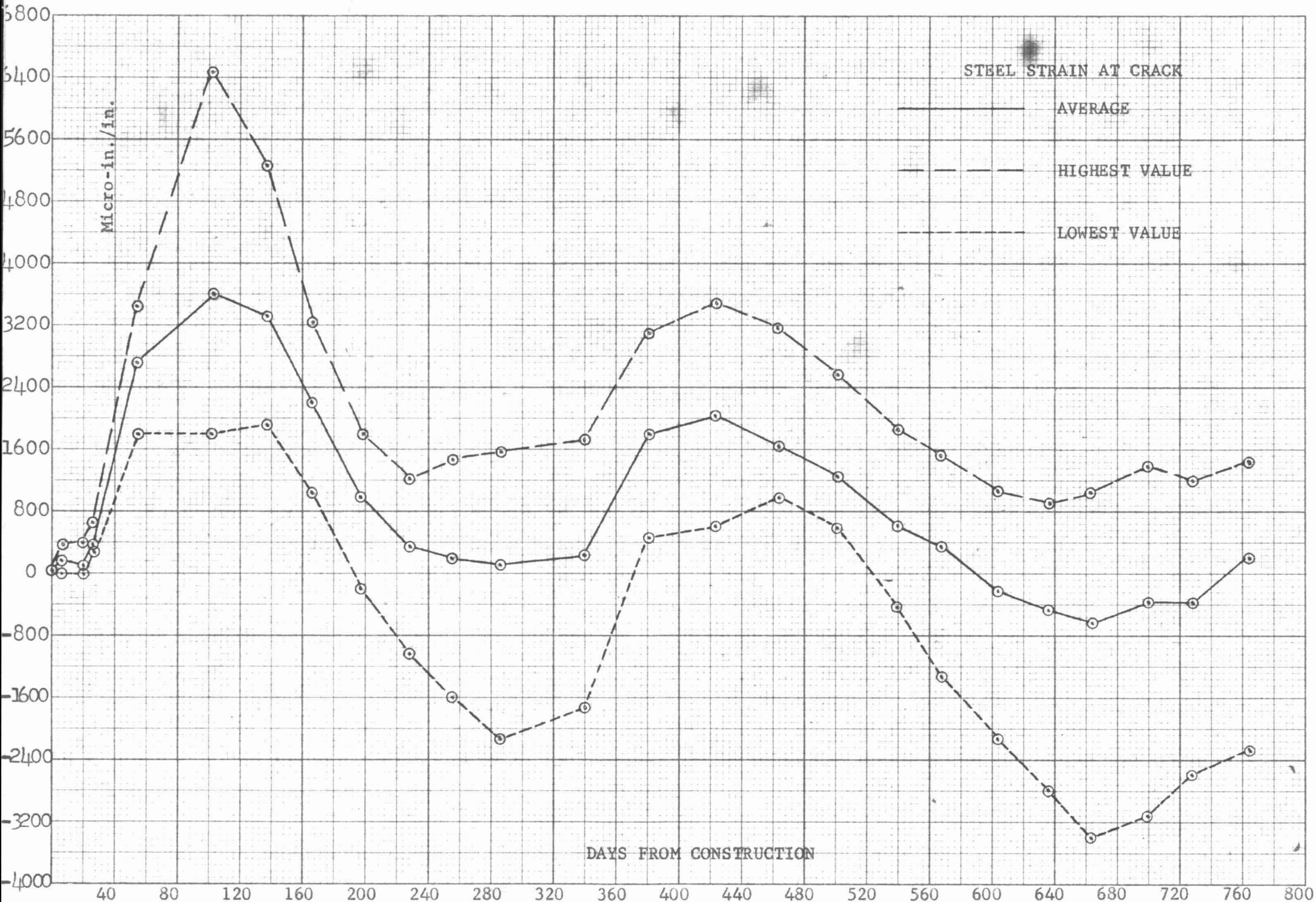

STEEL STRAIN AT CRACK
AVERAGE
HIGHEST VALUE
LOWEST VALUE
Micro-in./in.
6800
6400
5600
4800
4000
3200
2400
1600
800
0
-800
-1600
-2400
-3200
-4000
DAYS FROM CONSTRUCTION
40
80
120
160
200
240
280
320
360
400
440
480
520
560
600
640
680
720
760
800

FIGURE 5